Relationships among Plant Available Phosphorus, Fertilizer Sales, and Water Quality in Northwestern Ohio

Frank G. Calhoun,* Jerry M. Bigham, and Brian K. Slater

ABSTRACT

Soluble reactive phosphorus (SRP) in northwestern Ohio river water has declined over the past 20 yr in response to decreased applications of fertilizer P. Our objective was to evaluate changes in soluble P (Bray-1 P) levels in the soil over time as influenced by fertilizer P management, cultivation practice, soil properties, and landscape factors. Because soil is the intermediary between added P and SRP measured in river water, we examined the relationship between fertilizer P, soluble soil P, and SRP. Using historical soil survey sample sites as a baseline for original soluble P concentrations (P_{or}), we resampled Ap horizons to establish current levels of soluble P (P_{cu}). The P_{or} baseline extended from 1953–1982 and P_{cu} from 1996–1998. Thirty percent of the P_{cu} values and 17% of the P_{or} values were $\geq$40 mg kg^{-1}. Log-transformed means for P_{cu} were significantly higher than for P_{or}. The principal determining factors for P_{or} were physiography, soil texture, and soil series. Current P is affected by present tillage practice and drainage class. Change in soluble P in the soil is not as responsive to fertilizer P sales as is SRP in river water. This suggests that as fertilizer P sales decline, a declining percentage of P added as fertilizer is annually dissolved and transported into the drainage system. Soluble P in soil is governed by a combination of fertilizer and tillage management, soil properties, and landscape factors interacting over time.

In the early 1980s, a coordinated effort was initiated to reduce nonpoint sources of phosphorus (P) runoff into Lake Erie (Baker and Richards, 2002). Between 1971 and 1995 fertilizer P use has declined by 51% and 26% in the Maumee and Sandusky River watersheds, respectively. During the same period animal manure P additions to soil have declined by 24 and 35% for these watersheds (Richards et al., 2002a). Recent water quality assessments show that the P reduction programs have achieved measurable success. Richards and Baker (2002) report that soluble reactive P (SRP) concentrations have declined by 70 to 90% between 1974 and 1995. Logic suggests that the soluble P status of soils in the watersheds should mirror the decline in fertilizer P application and SRP levels in the rivers. The challenge is to uncover a method to test the hypothesis.

Several long-term studies on research plots have demonstrated a parallel relationship between levels of soluble or soil-test P and fertilizer P rates (Webb et al., 1992); however, the soils examined in such studies rarely reflected the range and complexity of soils and landscapes within the total watershed. Furthermore, plot studies have seldom represented the complete range of management practices in a watershed. Fields and small agronomic watersheds have also been studied, with an emphasis on the effect of management on spatial relationships of soluble P (Gburek and Sharpley, 1998), but long-term assessments of soil test P have not been conducted at this scale.

We were able to identify only one study that assessed P levels in the Maumee and Sandusky River watersheds at a given point in time. Logan (1989) analyzed 129 surface soil samples for total P, NaOH-extractable P, and Bray-1 P. Data were reported by soil series and encompassed soil samples collected throughout the Lake Erie basin of northern Ohio. Results indicated that total P, more so than soil test P, was highly correlated with clay content. Mean total P content by soil series ranged from 360 to 930 mg kg^{-1} with highest values for fine-textured soils. Mean concentration of Bray-1 P ranged from 13 to 50 mg kg^{-1}. Soil sample site locations were not provided; consequently, date of original sampling and cultivation conditions at the time could not be determined.

Another source of chronicled P data is the soil test laboratory files at Ohio State University (OSU). Ohio data can be grouped by year and zip code and should facilitate large watershed summary. Unfortunately, the zip code only identifies the location from which the soil sample was mailed to the laboratory and might not be the zip code in which the field was located. Many farmer field soil samples were consolidated by a fertilizer distributor and sent to the laboratory from a remote location. A second problem with OSU laboratory soil test data is that the number of soil samples submitted annually declined as farm operators increasingly turned to private laboratories for this service. This led to the termination, in 1998, of the OSU soil-testing program. Private labs in the region have only recently begun computer storage of soil test data (R. Warden, personal communication, 1999).

Ideally, benchmark sites for evaluating long-term trends in soil quality encompassing principal soil landscapes and agricultural management would have been established and regularly monitored over the past 25 years. Unfortunately, concerns about soil quality were not a high priority in the 1960s and 1970s. The soil characterization program in support of the progressive soil survey for Ohio (and elsewhere in the USA) offers a viable alternative to assess long-term trends in soil test P. This database, in addition to the archived soil samples, represents an untapped resource for potential use in evaluating long-term soil quality trends.

School of Natural Resources, The Ohio State University, Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, OH 44691-4096. Prepared as part of a grant from the USDA State Cooperative Research, Education and Extension Service (CSREES). Received 29 Aug. 1999. *Corresponding author (calhoun.2@osu.edu).

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Abbreviations: OSU, Ohio State University; P_{cu}, current concentration of Bray-1 phosphorus in the Ap horizon; P_{or}, original concentration of Bray-1 phosphorus in the Ap horizon; SOC, soil organic carbon; SRP, soluble reactive phosphorus in river water.

The objectives of this study were to (i) summarize historical soil test P data for northwest Ohio and (ii) return to the original soil survey sites and resample the Ap horizons for comparison of Bray-1 P levels with those of the archived soil samples. We propose that the soil is the intermediary between fertilizer and manure P and SRP measured in the river water. Furthermore, our hypothesis is that soluble P levels in the soil will reflect changes in fertilizer P management and changes in cultivation practices over time as affected by intrinsic soil and landscape factors. We will show that changes in soil test P levels are related to physiography, drainage class, soil texture, and tillage management. Finally, this study represents an effort to relate soil test P, fertilizer P sales, and soluble reactive P levels in river water over time.

MATERIALS AND METHODS

Description of Study Area

The study area consisted of all or part of 18 counties in northwestern Ohio. The Maumee and Sandusky Rivers drain the region and these watersheds are composed mostly of lake plains and glacial moraines. The lake plains represent high water stages of Lake Erie during the recession of Wisconsinan-age glaciers, and lake plain soils have developed from lacustrine clays and wave-leveled glacial till. At each stage a beach ridge developed on many of the shorelines, and beach ridge soils are typically very sandy. Ground moraines and ridge moraines occur in the upper reaches of the basins and are more sloping (mostly 2–6% slopes) than the lake plains (mostly <2% slopes). The cultivated soils on moraines typically have Ap horizons lower in clay content than the poorly and very poorly drained cultivated soils of the lake plains. Associated with the moraines and old lakeshores are locally important deltas and outwash plains with soils formed from water-worked, coarser-textured parent materials. Both the Maumee and Sandusky Rivers have extensive tributary systems with associated floodplains.

Ohio State University Soil Test Database

Electronically stored soil test data were available for 1977 through 1996. The database was queried for Bray-1 P and number of soil samples submitted by year and zip code. Zip codes were then matched with counties. Counties not within the study area were discarded. The data were then summarized by county and by year. A single yearly average for Bray-1 P for northwestern Ohio was then calculated.

Ohio Soil Characterization Database

The archived soil sample set precedes the accelerated adoption of reduced fertilizer P applications in the early 1980s and provides an incremental 30 yr baseline up to that date. The soil characterization program was initiated in northwestern Ohio in the early 1950s and continued until 1982. Some pedon (roughly equivalent to "soil profile") sampling has been reinitiated as soil surveys are modernized. Eighty-two percent of the pedons were collected prior to 1970. Following routine laboratory characterization, a subsample from each horizon was archived. Original pedon descriptions included a detailed description of the site location.

Over 600 pedons were described and soil samples were collected in the Maumee and Sandusky basins of northwestern Ohio as part of the cooperative soil survey program. Roughly 5% of the original soil sample sites have been lost due to nonagricultural development or inadequate descriptions of location. Approximately 65% of the original soil samples have been preserved. For this study, 319 pedon locations were identified that had both an archived soil sample and a viable resample site (Fig. 1). Routine laboratory characterization initially included particle size distribution analysis (PSDA) using pipette method 3A1 (USDA Natural Resources Conservation Service, 1996), soil organic carbon (SOC) using wet combustion until 1965 and dry combustion afterward, pH in water (1:1), and calcium carbonate equivalent (CCE) on soil samples where pH was greater than 7.2. Later, extractable bases, cation exchange capacity (CEC), and other refinements were added to the routine analyses but extractable P was never included. For the purpose of this paper, only the PSDA and SOC data are presented.

Field Methods

Using the original pedon descriptions, sites were located on county soil survey, topographic, road, and plat maps. Original site locations were described in terms of section number and position relative to landmarks. Landowners were contacted for permission to resample each location. Active or retired soil scientists who had led or participated in the original county surveys were employed to assist in site relocation. A measuring wheel was used to return as precisely as possible to the original site based on distances from landmarks or section corners provided in the pedon description. Resampling was conducted from 1996–1998 between the months of November and April in order to minimize the effects of recent crop management. A small pit was excavated to the base of the plow layer (Ap horizon). If there was obvious morphological change, two samples were taken from the Ap. This was frequently the case when the site had been under reduced tillage or in the Conservation Reserve Program. Thickness, depth, Munsell color, structure, root distribution, and consistence were described according to the Soil Survey Division Staff (1993). Soil samples were placed in cloth bags for transport to the laboratory. Site coordinates were measured to within 3 to 5 m using a global positioning system (GPS).

The current tillage system was estimated based on crop residues remaining on the soil surface. If the surface was at least 30% covered with crop residues then the site was classified as conservation tillage. If three different crop residues (normally wheat [*Triticum aestivum* L.), corn [*Zea mays* L.], and soybean [*Glycine max* (L.) Merr.]) could be identified then the system was assumed to be no-till. If the site was an abandoned field, pasture, or Conservation Reserve Program it was classed as meadow. A site was classified as conventional tillage when it was obvious that it had been moldboard-plowed in the autumn or if fresh, incorporated residue was noted while sampling the Ap.

Vegetation and land use was reported in the original pedon description using various terms including plowed, cultivated, meadow, pasture, grasses, and weeds. For analysis purposes, these designations were reduced to two categories: cultivated and meadow.

Laboratory Methods

Soil samples were dried at 40°C, ground, and passed through a 2-mm sieve. Material greater than 2 mm in size was discarded. The index of soluble P used in this study was the Bray and Kurtz P-1 test (soil to solution ratio of 1:10) determined from both the current (P_{cu}) and archived (P_{or}) soil samples as de-

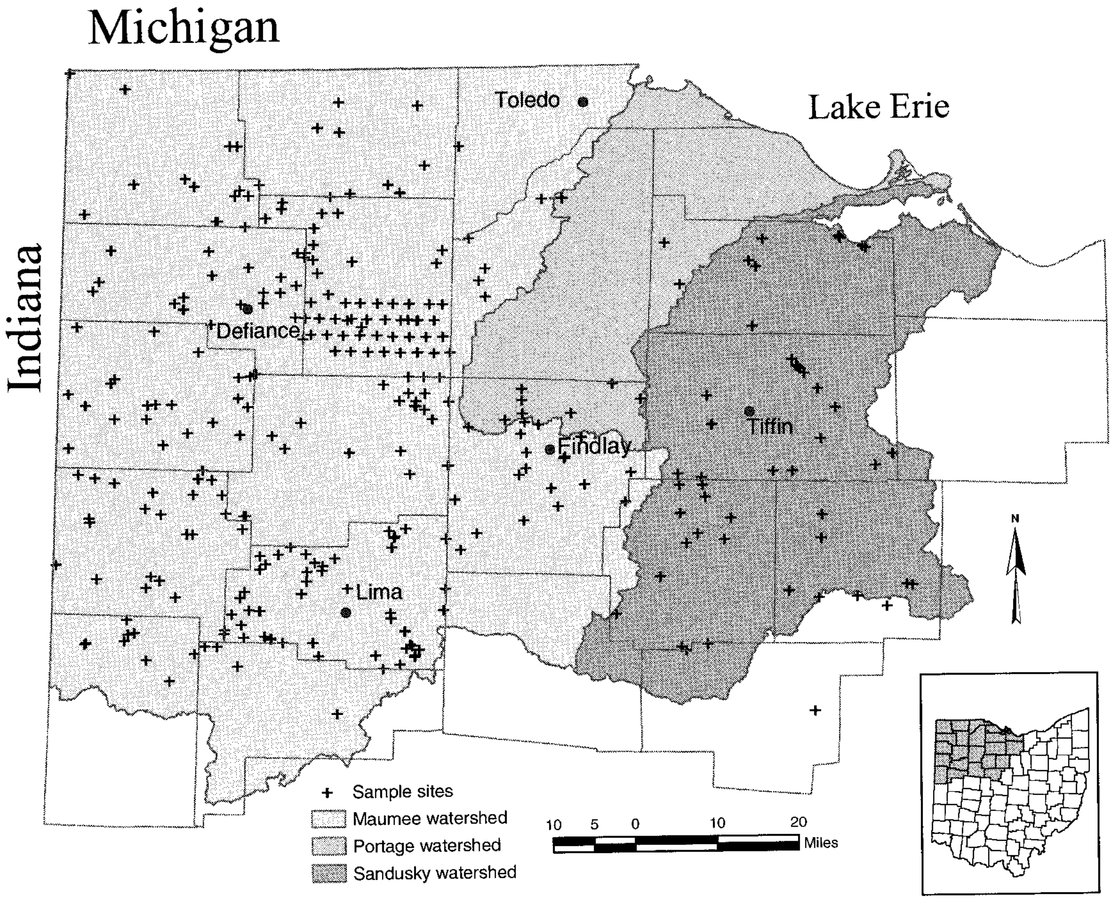


Fig. 1. Location of sample sites in northwestern Ohio.

scribed by the NCR-13 Committee (1998). Determination of soluble reactive P in river water is described in Richards and Baker (2002). Particle size data on the archived soil samples were obtained by pipette method 3A1 (USDA Natural Resources Convervation Service, 1996). Soil texture was assumed not to have changed significantly due to the dominance of level to nearly level slope classes in both watersheds. Data for Bray-1 P are reported in mg kg^{-1} soil.

Limitations of the Sample Population and Assumptions

Use of historical soil survey sites for sample collection does not assure an unbiased representation of the population of soil test P concentrations that exist in Ap horizons of northwestern Ohio. The rationale for selection of sites for investigation at the time depended on the classification and field correlation needs of the soil survey. In some cases the willingness of the farm operator to allow a pit to be excavated for this purpose was related to the operator's level of innovation in production agriculture and cooperation with soil and water conservation efforts in the county. It is possible that many of the soil survey pits were excavated on better-managed farms. It is also conceivable that this level of management did not continue from initial soil sample collection through present time.

Bray-1 P levels in surface soils are conspicuous for short-range spatial variability in cultivated fields. For this reason, soil samples submitted for testing are normally composited on a field-level basis. The original pedon soil sample was taken from an Ap or A horizon as representative of that horizon over a lateral distance of approximately 1 by 1 m with a total soil sample volume of 2 L. It was agreed that traditional soil

Table 1. Basic statistics of the population sample.

Variable	n†	Mean	Median	Minimum	Maximum	s‡	SE§
Original collection date	259	10 Aug. 1962	21 Dec. 1961	10 Apr. 1953	28 Apr. 1982	–	–
Sand, %	259	26.0	20.5	0	94.1	18.1	1.04
Clay, %	259	30.4	31.6	3.3	68.8	14.3	0.78
P_{cu}, mg kg^{-1}¶	259	36	28	5	159	26	1.6
P_{or}, mg kg^{-1}¶	259	26	22	6	121	17	1.1
Forest P, mg kg^{-1}¶	22	21	19	6	46	10	2.2

† Sample size.
‡ Standard deviation.
§ Standard error of mean.
¶ P_{cu}, current concentration of Bray-1 phosphorus in the Ap horizon; P_{or}, original concentration of Bray-1 phosphorus in the Ap horizon. Values are raw, untransformed means. Note that median values for P_{cu} and P_{or} are similar to $\log_{10}$ back-transformed means in Table 2.

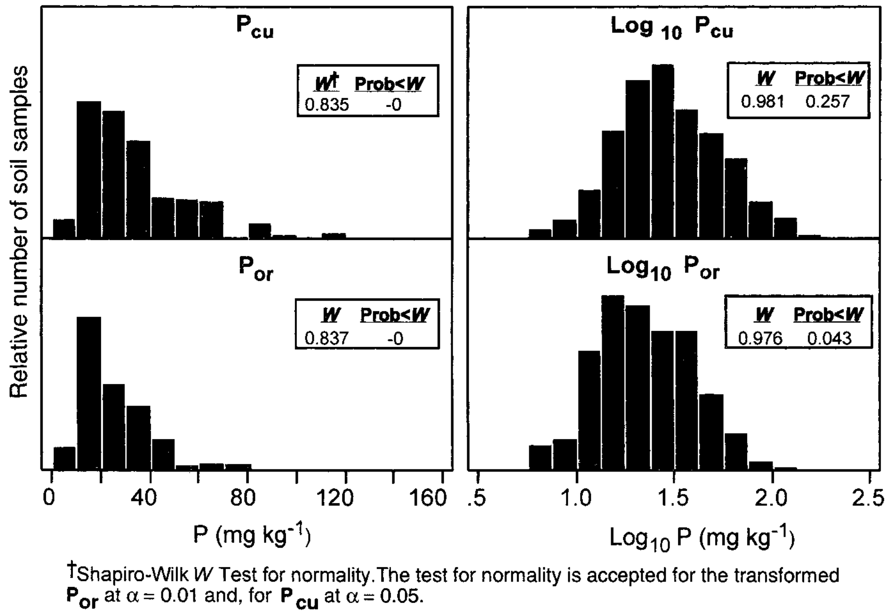


Fig. 2. Frequency histograms demonstrating the effect of $\log_{10}$ transformation on distribution of soil test P in soils of northwestern Ohio. The term P_{cu} represents the current concentration of P in the Ap horizon and P_{or} represents the original concentration (1953 to 1982) of P in the Ap horizon.

test sampling of the site should not be used and that the sampling procedure used during the soil survey should be followed. The original soil sample at the site was intended to be representative of the soil series as it occurred in that county but not of the field in which it was sampled. Our assumption is that the modern soil sample is representative of the specific location at which the original soil survey sample was taken.

Through the use of Mahalanobis analysis to identify outliers for P_{cu} and P_{or} (SAS Institute, 1996) and subsequent reevaluation of field location descriptions, 17 sites were discarded due to position near turn rows or suspected fertilizer spills. This reduced the sample size of the population to 302.

We assume that the samples are representative of the population of soil series found in northwestern Ohio (Richards et al., 2002a). In 1962, as part of a systematic evaluation of surface horizon and parent material texture, 45 sites of the Hoytville series (fine, illitic, mesic Mollic Epiaqualfs) were sampled in Henry County. Inclusion of all of these sites heavily biased the sample (26% of the total) toward glacial till–derived, very poorly drained soils collected during a short period of time. These soil samples were collected in transects along section-line roads in the lake plain area of the county and included only a topsoil sample and a subsoil sample. For these Hoytville sites the minimum, mean, and maximum values, respectively, were as follows: P_{cu} (12, 34, 88); P_{or} (8, 23, 68); and clay (30.9, 39.8, 48.6). We consolidated these sites into one averaged observation. The predominant current tillage was conservation as earlier defined in this paper. This reduced the sample to 259 observations, of which Hoytville now represented 16% of the total. This also brought the remaining soil series representation in the sample proportionately closer to that of the extent of soil series in the two watersheds. Predominant soil series in the two watersheds are Blount (fine, illitic, mesic Aeric Epiaqualfs; 19%), Hoytville (16%), Pewamo (fine, mixed, active, mesic Typic Argiaquolls; 10%), Paulding (very-fine, illitic, nonacid, mesic Typic Epiaquepts; 4%), and Glynwood (fine, illitic, mesic Aquic Hapludalfs; 4%). Approximately 125 series constitute the remaining 47% of the area. The sample population consists of the following proportions of soil series: Hoytville, 38 sites (16%); Blount, 30 sites (12%); Pewamo, 15 sites (6%); Paulding, 12 sites (5%); and Glynwood, 7 sites (3%). The remaining 157 sites represent 65 soil series.

Distributions of P_{cu} and P_{or} are exponential and the data were consequently $\log_{10}$–transformed. The exponential nature is explained by the effect of accelerated and nonuniform P fertilization over time. The effect is illustrated in Table 1, where the mean is greater than the median for P_{cu} and P_{or} by 29 and 18%, respectively. Generally, as the mean approaches the median, sample distribution approaches normality. Log-transformation resulted in a distribution much closer to normality (Fig. 2). All tests for statistical significance were done on log-transformed data and the means were then back-transformed. Nontransformed basic statistics for the overall sample population are shown in Table 1 in addition to surface soil samples collected from 22 forested sites that are provided for comparison with the cultivated sites. All references to statistical means are for those back-transformed from $\log_{10}$ transformation unless otherwise noted.

RESULTS AND DISCUSSION

Both fertilizer P sales and soil samples from farmer fields submitted to the OSU soil test laboratory (5000 in 1996) have declined at approximately the same rate from 1976 to 1996 (Fig. 3). The mean soil test P level for northwestern Ohio increased from 25 to 50 mg kg^{-1} during the same period (Fig. 3b). Data from a private laboratory for more than 24 000 soil samples submitted from Ohio in 1998 averaged 40 mg kg^{-1} (A&L Great Lakes Laboratories [Fort Wayne, IN], unpublished data, 1999). The A&L Great Lakes laboratory uses the Mehlich-3 method for phosphorus determination and employs a regression equation to convert Mehlich-3 P analysis results to an equivalent Bray-1 P value. Maintenance levels for Bray-1 P have been established at 15 to 40 mg kg^{-1} for corn, soybean, and wheat in Ohio, Michigan, and Indiana (Michigan State University Extension, 1995). There is very little agreement on environmentally critical levels of soil test P. There is agreement that soil test P is highly correlated with biologically available P and

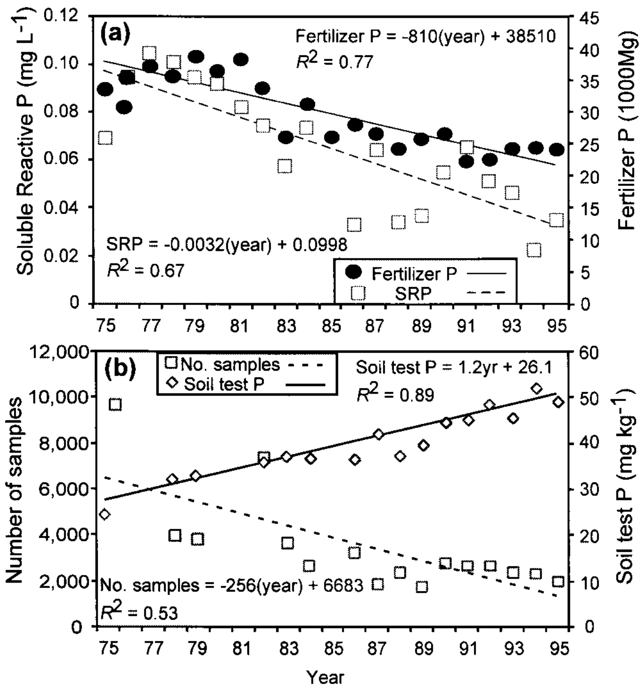


Fig. 3. Annual trends in (*a*) soluble reactive P (SRP) in river water and fertilizer P sales; (*b*) soil test P and number of soil samples submitted for analysis in northwestern Ohio.

equilibrium P concentration at zero sorption (Moore et al., 1998).

It is difficult to resolve the contradiction between decreasing fertilizer P use along with even more rapidly declining SRP concentrations in river water and steadily increasing soil test P levels in the soil samples submitted for testing at the OSU laboratory. This discrepancy suggests two possibilities: (i) increasing use of reduced tillage has decreased soluble P loss from cultivated fields, or (ii) most of the soil samples submitted for testing were to evaluate whether P levels were too high rather than too low. The second possibility is suggested by our data where mean P_{cu} level is substantially lower than that of the OSU soil test data reported in 1995.

The untransformed mean P_{cu} for all sites is significantly higher than it was at the time of original sampling between 1953–1982 (Table 1). Thirty percent of the P_{cu} values and 17% of the P_{or} are ≥40 mg kg^{-1}. This is a weighted average concentration for the complete Ap horizon. Median values for P_{cu} and P_{or} are 8 and 4 mg kg^{-1} less than the mean, reflecting the exponential distribution of the untransformed data. The present mean thickness of the Ap is 26% greater than it was at the time of the collection of the original soil survey sample. At the same time, P_{cu} is 38% higher than P_{or} and the mean concentration of P in the included soil below the original Ap is 14 mg kg^{-1}. Assuming no change in soil bulk density, there is 53% more soluble P now stored in the Ap horizon compared with that when it was originally sampled. If bulk density were greater now then this would result in an even higher estimate of stored soluble P.

As tillage is reduced, soluble P concentrations increase in the upper few millimeters of the Ap (Dick, 1983). Our data show that the mean concentrations (untransformed) of P_{cu} in the upper 10 cm of the Ap horizons of conventional and conservation tilled sites in this database are 40 and 49 mg kg^{-1}, respectively. The mean concentrations of P_{cu} in the 10- to 24-cm zone are 37 and 34 mg kg^{-1}, respectively. No-till sites are similar to the conservation till sites but have lower mean P_{cu} values of 37 and 22 mg kg^{-1} in the upper and lower Ap horizon, respectively.

Soil and Landscape Factors

Soil test P is nonuniformly distributed across the landscape. In addition to fertilizer and animal manure P applications, the intrinsic properties of the soil, slope, and vegetative cover affect the magnitude of soluble P.

Physiography

The land surface in northwestern Ohio is the result of geomorphic processes related to glacial till deposition, natural lake drainage and shoreline modification, littoral deposition, melt-water outwash from glacier edges, and modern erosion. These processes can have an effect on the initial pool of P in the underlying soil because they control chemical, physical, and mineralogical properties of the parent material. The P_{cu} is significantly higher than P_{or} in the Ap horizons of soils located on lake plains, ground moraines, and ridge moraines (Table 2). Mean separation, using the Tukey–Kramer Honestly Significant Difference test (SAS Institute, 1996), shows that P_{or} was significantly ($p \leq 0.05$) higher in the Ap horizons of soils on beach ridges and outwash plains. Following 15 to 45 yr of P fertilization, there is no significant difference in P_{cu} between physiographic classes.

Drainage Class

Drainage class connotes the length of time that a soil profile is saturated with water each year. This is closely related to landscape position in northwestern Ohio, and all drainage classes can occur on any physiographic surface. Very poorly and poorly drained soils are saturated for long periods each year and are generally located on the lowest landscape positions where internal drainage is restricted. Nearly 47% of the sites in this database are very poorly drained. For all drainage classes, P_{cu} is significantly higher than P_{or} (Table 2). In contrast to physiography, P_{or} was not significantly different among any of the four drainage classes. Somewhat poorly drained soils are significantly lower in P_{cu} than are well and poorly drained soils, indicating that P fertilizer application rates have been lower on somewhat poorly drained soils between the two sampling periods.

Soil Texture

Soil texture is an important factor in determining the magnitude of soil test P, and P_{cu} is significantly higher than P_{or} for all texture classes. Sandy Ap horizons have significantly greater levels of soil test P than the other texture groups that are higher in clay content (Table 2). Phosphorus application over the years has had the

Table 2. Basic statistics and statistical significance for current (P_{cu}) and original (P_{or}) Bray-1 P as affected by landscape, soil, and management factors.

Factor	n†	P_{cu} Mean‡	P_{cu} s§	P_{or} Mean	P_{or} s	P_{cu} - P_{or} t test	P_{cu} to P_{or} ratio
		mg kg^{-1}					
All sites combined							
	259	29	5.7	22	4.3	***	1.30
Physiography							
Floodplain	9	37a	7.3	23ab	3.4	NS¶	1.61
Beach ridge	15	36a	7.3	34a	6.6	NS	1.08
Outwash plain	27	35a	6.9	31a	4.8	NS	1.13
Lake plain	119	28a	5.4	21b	3.9	***	1.33
Ground moraine	69	27a	5.8	22ab	4.0	**	1.25
Ridge moraine	20	26a	4.1	18b	3.8	**	1.48
Drainage							
Well	22	36a	8.1	27a	5.3	*	1.36
Very poorly	121	31a	6.2	23a	4.1	***	1.35
Moderately well	36	30ab	4.6	21a	4.9	**	1.38
Somewhat poorly	80	24b	4.7	20a	3.5	**	1.21
Texture group							
Sandy	14	71a	9.9	47a	5.1	*	1.51
Coarse-loamy	42	32b	5.7	26b	4.2	*	1.27
Fine-loamy	109	26b	5.1	22b	4.3	*	1.17
Clayey	94	26b	5.1	19c	3.6	***	1.36
Soil series							
Pewamo	15	31a	6.1	27b	4.5	NS	1.15
Hoytville	38	30a	3.1	19ab	3.6	***	1.61
Latty	14	26a	6.1	19ab	4.8	NS	1.36
Morley	11	22a	7.5	13a	2.6	*	1.72
Nappanee	9	21a	3.8	16ab	2.3	NS	1.34
Blount	30	19a	3.9	17ab	2.3	NS	1.12
Paulding	12	17a	4.3	22ab	3.4	NS	0.76
Original tillage							
Cultivated	139	31a	6.4	23a	4.5	***	1.31
Meadow	120	27a	4.9	21a	3.9	***	1.26
Current tillage							
Conventional	47	35a	5.7	26a	4.2	**	1.35
Conservation	169	31a	5.7	22a	4.0	***	1.42
Meadow	19	24ab	6.4	22a	4.5	NS	1.09
No-till	24	15b	3.1	21a	5.2	*	0.72

* Significantly different column means (P_{cu} and P_{or}) at the 0.05 probability level.
** Significantly different column means (P_{cu} and P_{or}) at the 0.01 probability level.
*** Significantly different column means (P_{cu} and P_{or}) at the 0.001 probability level.
† Sample size.
‡ Means are back-transformed from $\log_{10}$ data; means followed by the same letter within columns and within a class are not significantly different according to Tukey–Kramer HSD ($p < 0.05$).
§ Standard deviation.
¶ No significant difference.

effect of decreasing differences in P_{cu} between soil texture groups. Clayey Ap horizons were typically fertilized at a higher rate so that P_{cu} is no longer significantly different from that of coarse-loamy Ap horizons. The rank of the means for both P_{cu} and P_{or} suggests that surface area is important in the buffering and magnitude of soil test P. Sandy and coarse-loamy Ap horizons are most common on beach ridges and outwash plains. Fine-loamy and clayey surface soils are prevalent on ground moraines and lake plains. Commercial vegetable production, accompanied by heavier fertilization than on grain crops, has traditionally been more prevalent on coarse-loamy and sandy soils in northwestern Ohio. In northwestern Ohio, both SOC and the clay content of Ap horizons increase as internal drainage decreases (Table 3). The SOC, in addition to clay, affects the proportion of labile P in soils. Soluble P is strongly adsorbed on both organic and inorganic colloid surfaces. Organic

Table 3. Soil organic carbon (SOC) and clay contents of northwestern Ohio soils as affected by drainage class.

Drainage class	n†	Mean‡	s§	SE¶
		mg kg^{-1}		
SOC				
Very poorly	236	2.21a	0.44	0.03
Somewhat poorly	129	1.58b	0.45	0.04
Moderately well	65	1.32c	0.41	0.05
Well	40	1.24c	0.59	0.09
Clay				
Very poorly	164	38.5a	11.3	0.9
Somewhat poorly	80	23.5b	9.2	1.0
Moderately well	36	18.7bc	6.7	1.1
Well	22	14.3c	8.4	1.8

† Sample size.
‡ Means followed by the same letter within the column are not significantly different according to Tukey–Kramer HSD ($p < 0.05$).
§ Standard deviation.
¶ Standard error of mean.

colloids are also strongly adsorbed on clay surfaces (Logan, 1989). The joint effect is, under equal rates of fertilizer P application, for very poorly drained soils to be more resistant to change in soil test P than better-drained, coarser-textured soils.

Soil Series

Specific ranges in physical, chemical, morphological, temperature, moisture, and mineralogical properties define a soil series. Seven of the more extensive series were selected to ascertain any changes in P at this categorical level. Only the Morley (fine, illitic, mesic Oxyaquic Hapludalfs) and Hoytville series had a mean P_{cu} significantly greater than P_{or} (Table 2). Hoytville is formed from wave-worked glacial till, is very poorly drained, has clay content of 30 to 45% in the Ap and occurs on lake plains. Morley is also formed from glacial till, has a lower clay content (15–30%), is well drained, and occurs on moraines. Mean separation shows that P_{cu} is not significantly different among any of the seven series. However, the P_{cu} to P_{or} ratio for Hoytville is much greater than that for Paulding, mainly because the latter is a very poorly drained lake plain soil derived from lacustrine clays. Paulding soils are seldom tile-drained because of the high clay content (≥60%), and Hoytville soils are nearly always tile-drained and have a higher SOC content. Based on this sample of the population of Paulding soils, it is evident that the inability to efficiently drain these soils has resulted in lower P fertilization rates as shown by a mean P_{cu} to P_{or} ratio of less than one. Correspondingly, the Hoytville series has a corn yield rating 40% greater than Paulding (Soil Survey Staff, 1997).

Tillage Management

The results in Table 2 indicate that fertilizer P application rates have been closely related to changes in tillage management. Tillage practices, especially current tillage, can be an indicator of fertilizer management. When categorized by original tillage practice, P_{or} is significantly lower than P_{cu} for both cultivated and meadow sites (Table 2). For the two original tillage practices, neither P_{or} nor P_{cu} are significantly different. When originally collected, between 1953 and 1982, 46% of the sites were meadow, reflecting a greater animal (primarily dairy and beef cattle and horses) population (Richards et al., 2002b). The 54% of sites classed as cultivated can be assumed to be the same as that currently identified as conventional tillage.

The P_{cu} is not significantly greater than P_{or} for sites currently classed as meadow (Table 2). The P_{or} is not significantly different between current tillage classes, indicating that the sites in each class represented a balanced set of physiographic positions, drainage, and soil texture. For P_{cu}, conventional and conservation tillage are significantly higher than no-till. There is no statistically significant difference between conservation and conventional tilled sites. Conservation tilled sites reflect a conventional tilled past and an assumption is made that initiation of reduced tillage was also accompanied by reduced fertilizer P rates. This appears to be the case.

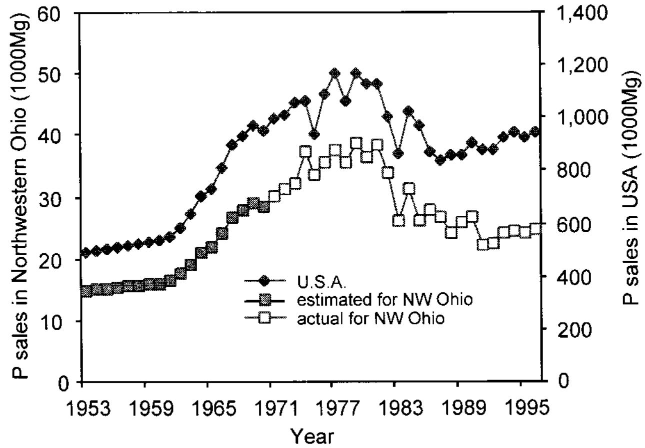


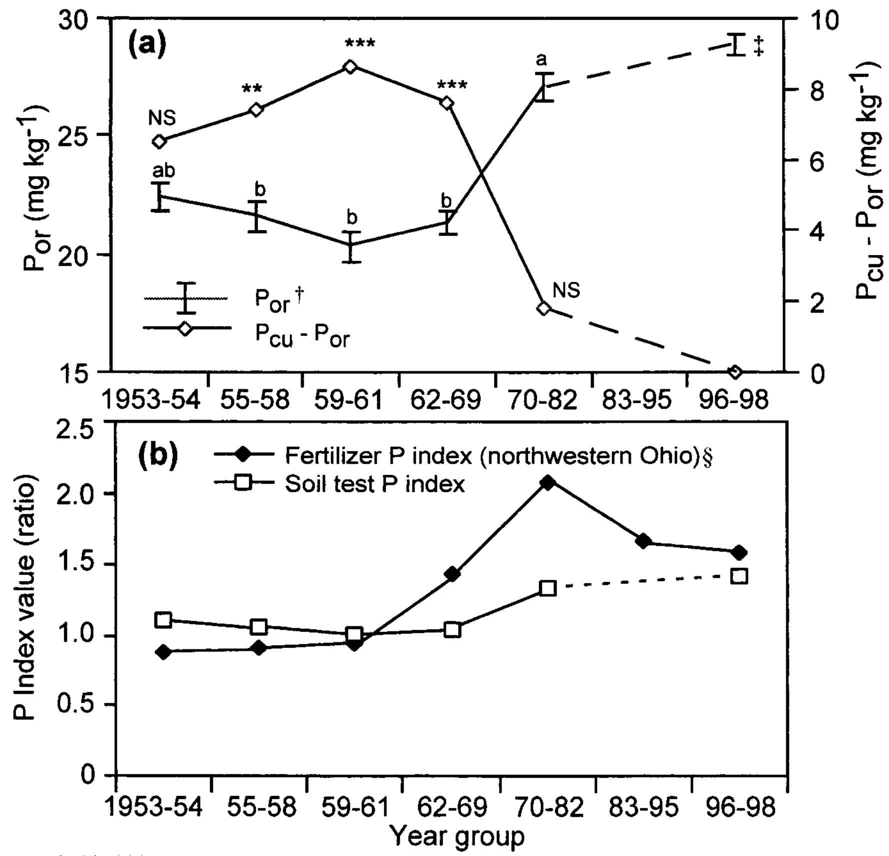
Fig. 4. Total annual fertilizer P sales, expressed as elemental P.

Changes with Time

Between 1960 and 1979 fertilizer P sales for the USA increased from 0.55 to 1.21 million metric tons in 1979 (Commercial Fertilizers, 1997). Nationally, the sale of fertilizer P for 1996 was 19% less than the amount sold in 1979 (Fig. 4). For northwestern Ohio, the decline has been much greater (44%) for the same time period. Neither county-level nor state-level fertilizer P sales records exist for Ohio prior to 1971. These were estimated from the national data by assuming that fertilizer P consumption in northwestern Ohio was proportionately the same as that of the USA between 1960 and 1970. In 1971, fertilizer P sales in northwestern Ohio accounted for 3% of the national sales, and this figure was used to calculate estimated annual amounts. Both nationally and in northwestern Ohio the greatest rate of decline in fertilizer P sales occurred between 1982–1984. In fact, fertilizer P sales in northwestern Ohio had declined 18% prior to the implementation of the P reduction program in 1982. It appears that operators began reducing fertilizer P applications in response to documented P buildup in the soil, energy economics at the time, and increasing concern about pollution of Lake Erie. National sales appear to be gradually increasing since 1990, but sales in northwestern Ohio have remained near the same level of consumption that occurred in 1965. The question is, do the Bray-1 P concentrations of Ap horizons in northwestern Ohio reflect these historical shifts?

Time series, moving averages, or smoothing procedures are not applicable to this data set because the soil samples were not collected on a regular and uniform basis over time. Consequently, the data were grouped into seven time intervals of roughly equal subsample observations for use of the Studentized *t* test of statistical significance.

Mean P_{or} declines for 1953–1961, rises slightly for 1962–1969, and increases sharply for 1970–1982 (Fig. 5a). This trend roughly approximates the buildup of fertilizer P sales from 1960–1970 and the maximum sales



*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively between means of P_{cu} and P_{or} for each year group; NS, nonsignificant at the 0.05 level. P_{cu} - P_{or} is the difference between the mean for P_{cu} and that for P_{or} within a given year group.

† Means for P_{or} followed by the same letter are not significantly different according to LSD (p<0.05). Error bars represent the standard error of the mean.

‡ The mean for P_{or} in 1996-98 is the overall mean for P_{cu}

§ The fertilizer P index for northwestern Ohio was calculated by dividing fertilizer P sales for a specific year by fertilizer P sales for 1960. The indexes were then averaged for each time period used in the analysis. Soil test P index = Mean P_{or} for time period / Mean P_{or} for 1959-61.

Fig. 5. Changes over time for (*a*) the original concentration of Bray-1 phosphorus in the Ap horizon (P_{or}) and the difference between means of the current concentration of Bray-1 phosphorus in the Ap horizon (P_{cu}) and P_o; (*b*) relative change in P_{or} compared with fertilizer P sales.

from 1974–1981 (Fig. 4). After 1982, there is a continued, but gentler slope to mean P_{cu} for the resampled period (1996–1998). The difference between P_{cu} and P_{or} steeply declines between 1962–1969 and 1970–1982 because the buildup of P was nearly complete in 1982. By 1982, P_{or} was approaching the same magnitude as P_{cu}. Mean P_{or} for 1970–1982 is significantly greater than the means for 1955–1969 but is not significantly greater than the mean for 1953–1954. The mean for 1996–1998 is that for P_{cu} and includes all sites.

In order to compare P_{or} and P_{cu} levels with fertilizer P sales, percentage changes were calculated using 1960 as a baseline (Fig. 5b). The comparisons imply that: (i) buildup of soil test P lags behind fertilizer P sales, (ii) crop uptake and soil sorption of soluble P partially compensated for the high fertilizer P added from the mid 1960s through 1980, and (iii) soil test P does not respond to declining fertilizer P rates as directly as does SRP in river water (see Fig. 1a).

Not all of the fertilizer P will be fixed by soil colloids or assimilated by plants. The high correlation between fertilizer P sales and SRP in river samples (Fig. 3a) suggests that an annual percentage of added P is dissolved and moves primarily by surface flow into the drainage system. Tile drainage may also contribute a portion of the SRP. Soluble reactive phosphorus is declining more rapidly than total phosphorus in river water (Baker and Richards, 2002), and this suggests that as added P has declined, this has freed remaining fixation capacity of the soil. The slightly greater negative slope for SRP compared with fertilizer P (Fig. 3a) supports this conclusion, although sorbed P was not measured in our study. The effects of changing fertilizer P application methods and tillage practices and seasonal runoff are further discussed as contributing factors by Baker and Richards (2002). This trend supports the conclusion of Baker and Richards (2002) that net accumulation of P has declined in these soils over the past 20 yr and is reflected in soil test P.

CONCLUSIONS

Based on this sample population the following can be concluded about Bray-1 P concentrations of Ap horizons in northwestern Ohio:

(i) The current mean concentration of Bray-1 P (P_{cu}) is significantly greater than the original concentration (P_{or}) when all sites were considered.
(ii) The magnitude of P_{or} was related to physiographic surface, but this effect was eliminated by increased fertilizer P applications during the 1970s.
(iii) Mean P_{or} was not significantly different among soil drainage classes, but P_{cu} was significantly higher for well-drained and very poorly drained soils. This suggests that drainage class has influenced decisions on fertilizer P rates.
(iv) Particle size distribution modifies the magnitude of soluble P and the effect of fertilizer P. Sandy Ap horizons were significantly higher in Bray-1 P. This does not imply that sandy soils have greater total P. A lower buffering capacity is probably involved in explaining this effect. Additions of fertilizer P, however, have reduced the difference in P_{cu} among all texture classes except sandy soils.
(v) Fertilizer P management was affected by soil series. A soil series represents a confined range of physiography, drainage, and particle size. For example, not all soil series within the same drainage class were fertilized at the same rate.
(vi) Current tillage practice has a significant effect on the magnitude of P_{cu}. No-till soils have significantly lower P_{cu} concentrations than conventional and conservation tillage. Fertilizer P management has been influenced by tillage practice.
(vii) Bray-1 P significantly increased during the 1970s and early 1980s in response to high rates of fertilization. The rate of increase lagged behind that of fertilizer P due to crop uptake and, presumably, adsorption of P on colloid surfaces. Change in soluble P in the soil is not as responsive to fertilizer P sales as is SRP in river water. The close relationship between fertilizer P sales and river SRP suggests that a persistent, but declining, percentage of added P annually moves into the drainage system.

This study shows that soluble P in the soil (indirectly measured as Bray-1 P) is controlled by a combination of fertilizer and tillage management, soil properties, and landscape factors interacting over time. Former soil survey sampling sites are an underutilized resource for reconstructing environmental history and for observing temporal change in soil properties and environmental quality. Soil survey sites are important because they are referenced in both space and time, and can therefore serve as benchmarks. The archived soil samples from these sites are a source of baseline chemical data collected across time. The value of these data is enhanced by access to accessory information including detailed morphological and site descriptions and a variety of other standardized analytical data, permitting assessment of environmental changes that affect both soil and water quality.

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